The Effect of Ductile-Lithic Sand Grains and Quartz Cement on Porosity and Permeability in Oligocene and Lower Miocene Clastics, South China Sea: Prediction of Reservoir Quality[1]

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Ductile, clay-rich sand grains control porosity and permeability in the fluvio-deltaic Oligocene and lower Miocene sandstones of the South China Sea. Ductile grains account for between approximately 5 and 50% of the original sand grain population. There is a pronounced loss of porosity with increasing burial depth in the basin. At depths of less than 3000 m this is due solely to ductile grain compaction where the rate of porosity loss with depth increases with increasing ductile grain content. At depths greater than 3000 m, the steep porosity loss with depth is due to combined ductile grain compaction and quartz cementation. The amount of quartz cement increases with increasing burial depth; however, cleaner sandstones tend to have greater amounts of quartz cement at any given depth below 3000 m. This leads to convergence of porosity evolution for the clean and ductile-rich sandstones below 3000 m. There is a rapid loss of permeability with decreasing porosity because compaction of ductile grains smears them between rigid quartzose grains leading to blocked pore throats. A consequence of this process is that the lowest permeabilities are found in sandstones with the highest ductile grain contents. Quartz cement does not have a clear and discernible control on permeability. The pronounced loss of porosity with increasing depth and permeability with decreasing porosity leads to low permeability at relatively shallow burial depths. Reservoir quality is thus controlled by the nature of the primary sand and depth of burial. The sediment supply system led to systematic changes in ductile grain content across the basin with ductile content increasing into the more distal part of the sediment system. The consequence is that depth of economic basement (in terms of porosity or permeability) can be predicted as a function of ductile grain content and burial depth for prospects across the basin.

INTRODUCTION

Reservoir quality (by which we mean porosity and permeability) is a critical parameter to the economics of any endeavor in oil and gas exploration and production. Porosity has a major effect on petroleum in-place calculations for a prospect. Permeability has a major effect on the rate at which petroleum can be produced. All other factors being equal, flow rate from a well is proportional to the permeability of the reservoir. The critical porosity (for a given trap volume) and permeability (for a given sand-body thickness) for economic viability will naturally vary depending on the license, marketing opportunities, and engineering infrastructure. Because these three variables are often known or predictable before or during the exploration phase, it is possible to establish minimum economic porosity and permeability values (for estimated trap volumes and sand-body thicknesses). These then become targets against which explorers can rank items in the prospect inventory.

The role of lithic grains on compactional porosity loss has been recognized for a long time; however, lithic grains only exacerbate the rate of porosity loss with depth if they are ductile-lithic or plastically deformable grains. Quartzose lithic grains, such as polycrystalline quartz grain, behave in much the same way as monocrystalline quartz grains upon burial and compaction (although chert grains tend

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to be fairly reactive leading to enhanced pressure solution relative to macrocrystalline quartz grains). The role of ductile-lithic sand grains on the permeability evolution of sandstones has only recently been acknowledged in principal. The sandstones under examination are Oligocene and lower Miocene, fluvial to shallow marine (deltaic) deposits from the South China Sea. Tertiary sandstones in the South China Sea and neighboring basins often have reservoir quality problems (Worden et al., 1997). The economic basement in the South China Sea is generally shallower than other worldwide clastic basins, for example, compared to reservoirs being explored at depths of 5000 m and more in the Gulf of Mexico and North Sea basins. In this paper, we seek to understand the depth limits for viable reservoirs in lithic-rich South China Sea basins.

Reservoir quality prediction is often performed using simple regression through porosity and permeability data. We have adopted a rational alternative approach by examining the fundamental controls on porosity and permeability (at a wide variety of scales), comparing the observed controls to theoretical models for porosity and permeability, and looking at how those controls vary stratigraphically with burial depth and with geography. This approach leads to predictions based on modeling and understanding rather than simple regression.

BACKGROUND GEOLOGY

Sediment Supply and Basin Origin

Paleogeography and sediment provenance were dominated by rifting to the east of the South China Sea and the growth of orogenic belts in the hinterland to the north west (e.g., the Himalayas and other orogenic belts). Thus there was a substantial basin developing at the same time as large-scale weathering, erosion, and transport of material occurred from the newly formed mountains. Sediment supply was broadly from northwest to southeast, although the main supply route of sediment in the Oligocene and lower Miocene was formerly along what is now the Gulf of Thailand rather than via the present day Mekong (Figure 1) (Matthews et al., 1997). The rift basin was filled with material derived from the Himalayas and related mountain belts, and the area of the South China Sea witnessed a variety of depositional environments depending on the local relative rate of subsidence vs. sediment supply. For most of the Oligocene and lower Miocene, however, the South

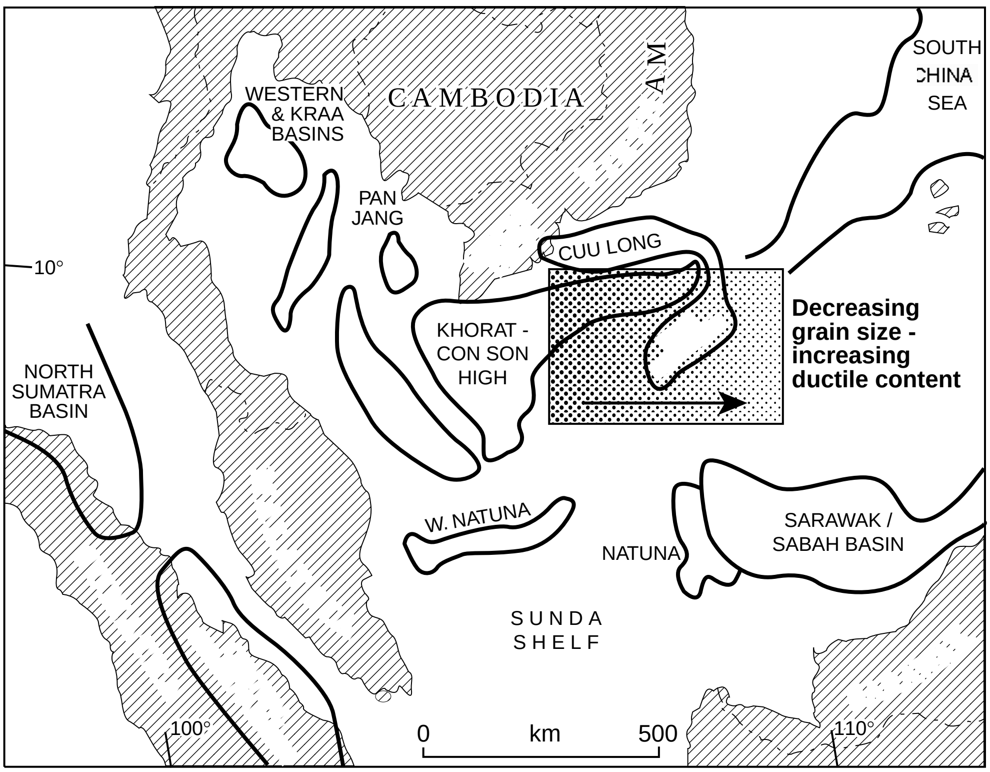

Figure 1—Location map of southeast Asia and the South China Sea showing the main sedimentary basins. The area under investigation is shown as a shaded box. There is a general trend of decreasing grain size from the western side of the box toward the eastern side. In the far western part of the study area, the average grain size is about 500 μm, progressively decreasing to about 125 μm at the far eastern side. This variation probably reflects distance from sediment source. Ductile content varies inversely with grain size so that ductile grain content also decreases from west to east across the study area. Location map adapted from Matthews et al. (1997).

China Sea is thought to have been mostly limited to delta-top type facies ranging from shallow marine through to fluvial/distributary channel-related facies (Matthews et al., 1997).

Burial and Thermal Histories

The South China Sea has undergone broadly continuous burial from the Eocene through to the present day (Figure 2a, b). There were periods of more and less rapid burial, but there were essentially no periods of uplift and erosion. The basin is still in the phase of rifting and has not reached any sort of pseudo-steady state or thermal subsidence phase.

The heat flow is presently between 35 and 40 mW/m^2, typical of rifted basins, leading to approximate geothermal gradients of about 30–37°C/km (Figure 2c). The heat flow is likely to have been greater soon after the onset of rifting, but the combined influences of transient temperature effects and continual subsidence suggest that the temperatures experienced by the Oligocene and lower Miocene sedimentary rocks are at their maximum at the present day.

METHODOLOGY AND SAMPLES

The specific sedimentology of the sandstones under examination was defined using classical core description (grain size, fabric, sedimentary and tectonic structures, carbonate cement distribution, etc.). This was combined with a simple analysis of the wireline logs, in terms of sequence architecture, to develop a picture of the overall depositional environment for the Eocene–lower Miocene succession.

Wireline data were collected from 11 wells from across the basin. Four cored wells were examined in detail using petrography and geochemistry. Core samples were taken from approximately 2300 to 4000 m depth.

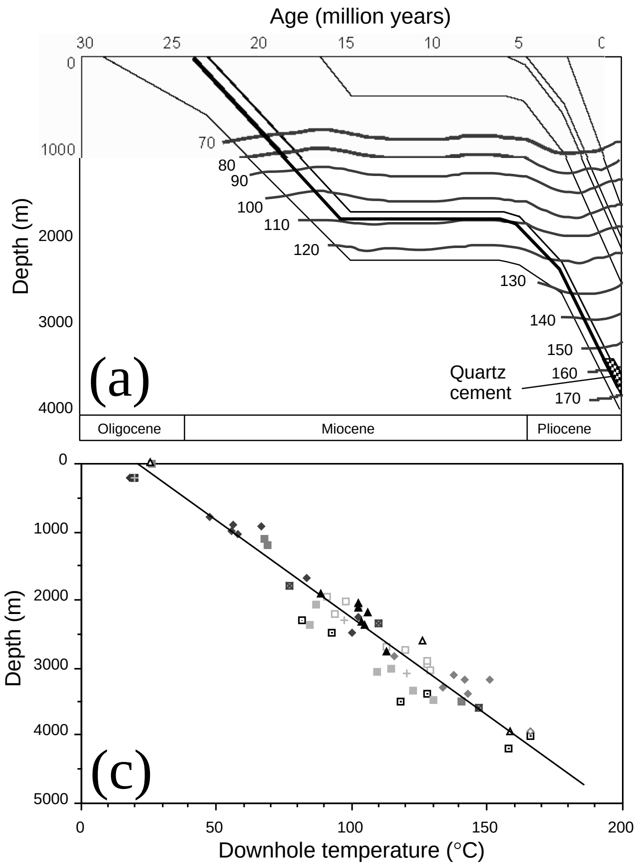

Figure 2—(a, b) Generalized burial and thermal histories for two wells from the South China Sea. Isotherms have been constructed to account for transient thermal effects, sediment compaction, varying heat flow during rifting, and varying water depth (and thus temperature of the sediment surface). (c) Regional depth-temperature data used to construct a general isotherm.

Petrographic analysis was performed on approximately 100 samples using a combination of routine optical microscopy on carbonate- and feldspar-stained thin sections, scanning and backscattered electron microscopy, and cathodoluminescence microscopy. All thin sections were point counted to quantify the various detrital and diagenetic mineral and grain populations. Two hundred solid counts per section were recorded with a separate channel for porosity. Quantitative bulk mineralogy was determined by whole rock and clay-separate x-ray diffraction.

Fluid inclusions in quartz were initially classified by the host mineral. The relationship to cement growth and identification of fluid type were done using standard transmitted light and UV petrography. A step-heating and temperature cycling methodology was adopted to ensure that the exact temperatures of last ice melting and homogenization were recorded (Roedder, 1984).

Petrophysical properties were determined from several hundred samples using conventional helium porosimetry and Klinkenberg-corrected gas permeametry. Porosity data were also calculated from continuous sonic transit time data (corrected to core porosity) using the Wyllie (time-average) method (Hearst and Nelson, 1985). An upper V_{shale} limit (derived from the spectral gamma ray tool) was placed on the sonic transit time data to ensure that mudstones were not included in the data set.

Porosity-permeability-depth data were compared to previously published, modeled trends for the effects of different diagenetic processes on porosity and permeability. The trends were drawn from work by Bryant et al. (1993), Evans et al. (1993), Cade et al. (1994), and Worden et al. (1997) to develop an understanding of porosity-depth and porosity-permeability patterns.

RESULTS

Sedimentological Context

Extensive paleontological analysis showed dominantly nonmarine to marginal marine environments with occasional thin, more fully marine intervals (Matthews et al., 1997). Routine core description led to the identification of a variety of facies. These included conglomerates (devoid of obvious structures at the core scale) and structureless, medium- to coarse-grained sandstone and fine to medium cross-bedded sandstones. The two most predominant facies are the medium-grained structureless sandstones and the finer grained cross-bedded sandstones. A variety of vertical log profiles are developed with blocky and fining-upward sands common, although coarsening-upward profiles are locally present in the more marine-influenced parts of the stratigraphy. The environment of sediment deposition, consistent with these fabrics, was probably delta-plain with local environments ranging from fluvial through to embayments and restricted shallow marine depending on the accommodation space-sediment supply equilibrium at the time of deposition (Matthews et al., 1997). There is limited bioturbation and no visible pedogenesis in the sandstones in the cored intervals. Minor depositional matrix is present, particularly in the finer grained rocks. No macroscopic stylolites were observed in core despite the abundance of clay and the relatively great burial depth (up to 4000 m) of some of the cores.

Average grain size measured from core, sidewall cores, and cuttings shows a general decrease from the western side of the study area toward the eastern side (Figure 1). This change probably reflects proximity to sediment source because the sediment was supplied by precursors to the Mekong flowing down what is now the Gulf of Thailand (Matthews et al., 1997).

Petrography

Detrital Sand Qualities

The sandstones are generally fine to medium grained. Quartz and lithic grains dominate the

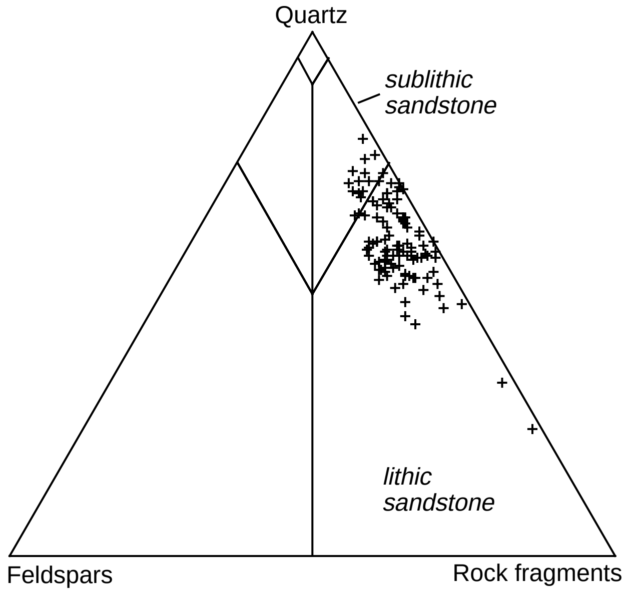

Figure 3—Sandstone ternary diagram illustrating abundance of lithic grains in South China Sea sandstones (diagram after McBride, 1963).

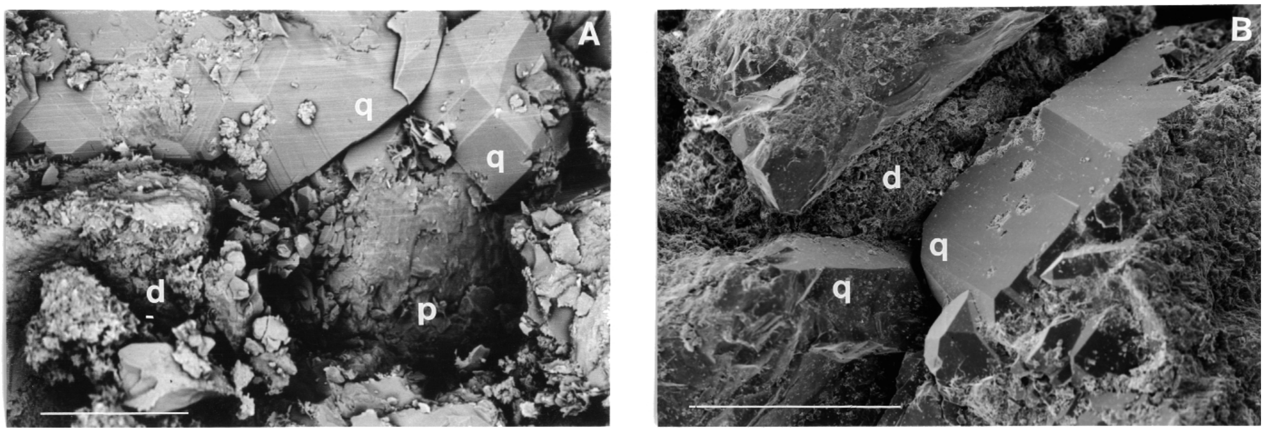

Figure 4—Scanning electron microscope images of high- and medium-ductile content sandstones. In both images, d = ductile lithic grains, q = quartz cement, p = polycrystalline detrital quartz grain. (A) (17% porosity, 20 md permeability, and 8% ductile grains) clearly visible intergranular macroporosity. The polycrystalline quartz grain has failed to grow thick quartz cement layers. (B) (8% porosity, 1.8 md permeability, and 15% ductile grains) contains a ductile grain (d) being squeezed between two quartz cemented rigid grains. The ductile grain has effectively closed the pore throat leading to much reduced permeability.

detrital mineralogy of the sandstones (Figure 3). The feldspar population tends to be negligible (less than 5%). The quartz grain population is dominated by monocrystalline quartz, but with a significant quantity of polycrystalline grains, presumably of metamorphic origin. The lithic grain population is dominated by clay-rich ductile rock fragments (Figure 4). It is difficult to define their precise origin because in many cases they have undergone varying degrees of neomorphism and deformation between the rigid quartzose grains. Most of the sandstones appear to have low depositional matrix clay contents, although in some cases deformed and recrystallized lithic grains have the misleading appearance of clay matrix (i.e., pseudomatrix). The grain size of the sandstones ranges from about 100 to about 500 µm with a mean of about 250 µm (Figure 5). The sandstones show a variety of degrees of sorting from moderately well sorted through to poorly sorted with no relationship to primary sand composition. There is a moderate inverse correlation between grain size and ductile grain content. The coarser grained (and structureless) sandstones tend to have low ductile contents, although the finer grained (cross-bedded) sandstones can have both high and low ductile contents (Figure 5). As a consequence, sandstones in the western portion of the study area have a higher ductile grain content than those in the eastern portion of the area (reflecting the grain size distribution discussed and illustrated in Figure 1).

The only definable results of very early diagenesis are highly restricted carbonate cements of limited volumetric significance. These fill locally the intergranular porosity and are identifiable on wireline logs as pronounced deviations on sonic logs. At relatively shallow burial depths (1000 m), porosity values are typically of the order of 30% (Figure 7a).

Changes During Diagenesis

Later diagenesis resulted in a several changes to the nature of the sediment. In many cases, the lithic grains were deformed between the less plastic quartzose grains. In such cases, they became smeared over the surfaces of the rigid grains and were squeezed into pore throats (Figures 4 and 6). In addition, these lithic grains also underwent varying degrees of recrystallization, which in some cases led to locally developed redistributional, secondary, intragranular microporosity. At progressively greater burial depths, porosity has been systematically reduced in terms of both maximum and mean values (Figure 7a).

Quartz cement occurs in samples at depths greater than about 3000 m (Figure 7b). This equates to a minimum temperature for quartz cementation of about 125–140°C. The maximum amount of quartz cement increases with increasing burial depth; however, depth (and thus temperature) is not the only control on quartz cementation because there is a wide range of volumes of quartz cement at any given depth (below 3000 m). Although there are no macrostylolites visible in core, there are microstylolites between individual quartz grains. These are visible as darkened sutures of complex morphology representing the interpenetration of grains. The darkened seams are clay